Design and analysis of a reconfigurable discrete pin tooling system for molding of three-dimensional free-form objects

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ABSTRACT

This paper presents the design and analysis of a new reconfigurable tooling for the fabrication of three-dimensional (3D) free-form objects. The proposed reconfigurable tooling system comprises a set of matrices of a closely stacked discrete elements (i.e., pins) arranged to form a cavity in which a free-form object can be molded. By reconfiguring the pins, a single tool can be used in the place of multiple tools to produce different parts with the involvement of much lesser time and cost. The structural behavior of a reconfigurable mold tool under process conditions of thermoplastic molding is studied using a finite element method (FEM) based methodology. Various factors that would affect the tool behavior are identified and their effects are analyzed to optimally design a reconfigurable mold tool for a given set of process conditions. A prototype, open reconfigurable mold tool is developed to present the feasibility of the proposed tooling system. Several case studies and sample parts are also presented in this paper.

1. Introduction

The current market trend is moving towards mass customization [1,2] in which every product can be customized to meet customer needs. However, a large class of material shaping processes such as forming, molding, casting rely on a long precursor of design and manufacturing of dies and molds. For instance, design and production of complex molds to be used in manufacturing of the interior components of an automobile may cost $0.5 million and require 6–9 months [3]. This paper presents a new methodology in design and analysis of reconfigurable tooling for the fabrication of highly customized three-dimensional (3D) complex objects without requiring any tool shaping process.

The proposed reconfigurable tool consists of one or more matrices of discrete pins in which top surfaces of pins approximate the actual tool (a die or a mold) profile as shown in Fig. 1. Different tool configurations can be achieved by changing the pin locations relative to each other, which eliminates the need for multiple tools. Such a tool would help reducing the cost and time required for designing and fabricating molds for variants of existing products. The tool proposed in this work is an assembly of reconfigurable pin matrices that form a cavity in which parts can be molded.

Due to high pressure and temperature conditions of molding and the discrete nature of reconfigurable tooling, there is a possibility of gaps opening up in between the elements of the tool. These gaps would be similar to the cracks or flashes in conventional molds through which molten material can leak and lead to the failure of the reconfigurable mold tool. Due to its discrete nature a reconfigurable mold tool would be structurally weaker than an equivalent solid die. Therefore, reconfigurable discrete tools need to be designed and analyzed, so that 3D free-form objects can be manufactured without the occurrence of gaps (flashes on the product surface).

The design of the reconfigurable mold tool is proposed based on its structural behavior under process conditions. Many methods of constraining the tool deflection such as external clamping forces, supplementary support blocks for the pin matrices and the pins are researched. The individual as well as the interactive behavior of the pins are studied in detail using a finite element method (FEM) based methodology to determine if any configuration of the pins would be free of gaps and leakages under given process conditions. This is done using the worst case of loading of a single pin in a row of pins and of an entire row of pins.

This paper aims at the development of a reconfigurable tooling system to manufacture solid free-form objects and to ascertain the tool capability under process conditions of molding. Section 2 presents a literature review of various discrete tooling systems.

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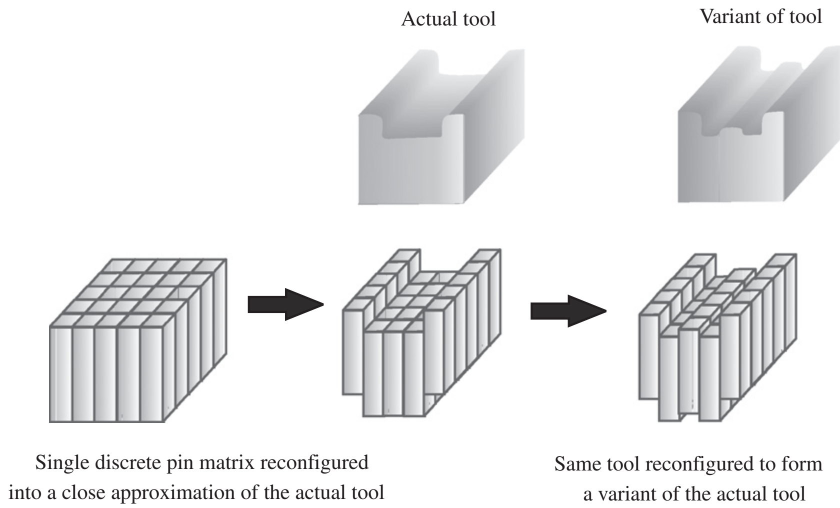


Fig. 1. The reconfigurable tool concept.

Section 3 presents the design of the reconfigurable mold tool based on its structural strength. Section 4 presents a finite element method (FEM) based structural analysis procedure to study the tool behavior under various process conditions. Section 5 details the computer implementation of the structural analysis in the form of several examples. This chapter also illustrates the concept of reconfigurable solid object molding using a prototype apparatus and presents example implementations. In Section 6, the conclusions of the research work and future research are presented.

2. Literature review

Discrete element-based tooling systems are relatively new members of the rapid, low-cost production tooling family. The main characteristic of these tools is that they are assemblies of discrete elements in contrast to conventional tools that are made of a single solid element. This discrete nature of these tools helps them to be reconfigured into multiple configurations enabling a reduction in the cost as well as time required to develop new tools.

In the literature, a single surface approximation using a discrete tool with a matrix of pins has been used for forming processes. Walczyk and Hardt [4] dealt with the application of reconfigurable tooling to sheet metal forming. As a part of this work, a generalized procedure of design was formulated after a thorough understanding of the forces that would act upon the tool to deform it. Key issues like pin shapes, clamping forces, stresses developed in the tool were addressed from an analytical point of view.

Walczyk et al. [5] and Munro et al. [6] developed a reconfigurable mold tool for incremental composite forming with application to the aircraft industry. Vacuum and convective heating were used along with a reconfigurable tool to provide shape to the raw material. To prevent dimpling of the surface of the product, due to the discrete nature of the tool, an elastomeric interpolating layer is also introduced in between the tool and the product material.

A multi-parameter design study carried out by Kleespies and Crawford [7], using theoretical, numerical, and experimental results explored the feasibility of building prototype thermoplastic compound curved surface parts with a variable molding process. Fundamental design relationships were provided for a variable geometry thermoforming model as a function of the surface quality and the minimum achievable radii of compound curvature. A rubber interpolator was also used to improve the approximation produced by the tool.

Laminate tooling system uses a row of layers or sheets of material in the form of discrete laminations. The laminates are held together tightly temporarily with bolts, clamps or permanently with riveting, brazing, soldering and the top surfaces of the laminates are used to form the part surface. Dickens [8] was one of the first to lay down design rules for laminate tooling in the form of heuristics for application in sheet metal blanking, stamping, forming and plastic molding. These covered laminate orientation direction, conformal cooling channels, laminate thickness and behavior of the laminate tool under process loads. Pepelnjak and Kuzman [9] developed an optimization model for the design of a layered or laminated tooling system to be used for forming and integration with a finite element method (FEM) analysis. The FEM analysis done to study the effects on tool under process load conditions assumed the tool to be solid for simplification purposes and instead of an assembly of layered elements. Work done by Soar and Dickens [10] dealt with pressure die casting, where an unbonded laminate tool was iteratively investigated using experimentation to determine the design limits of the laminate tool. Profiled edge lamination (PEL) tooling is a type of laminate tooling introduced by Walczyk and Hardt [11] in which the top surface of the laminates are beveled and profile machined to improve conformation to the intended tool surface. Im [12] developed three-structural models of the PEL tool to analyze its behavior under process loads. This was the first attempt to study the structure of a laminate tool as an assembly of elements and not as a solid body. The three-structural models were compared with results from experimentation and FEM analysis. Further, Shook [13,14] observed that the work done by Im [12] used two-dimensional (2D) models for simplicity purposes and assumed the loads to be one-dimensional that were actually three-dimensional (3D) in nature.

Several works have also detailed the use of various mechanisms to actuate the discrete pins in a reconfigurable tool. The use of a hydraulic-based mechanism was investigated experimentally for use with a closed as well as an open loop control system by Walczyk [15,16] with application to sheet metal forming. For sheet metal forming, Im et al. [17] experimentally tested and compared three pin actuation schemes namely a lead screw-based sequential setup unit (SSU), a hydraulically actuated (HA) mechanism and a shaft-driven lead screw (SDL) system for factors such as setup time, positioning accuracy and load bearing capacity. Reconfigurable tooling has also been researched and used for work piece fixturing [18].

Most of the research done till date regarding reconfigurable discrete pin tooling systems have been focused on the development of tooling for workpiece fixturing, sheet metal forming, vacuum forming and composite material forming. All these applications involve the approximation of a 2D surface. Other possible applications of this technology for processes that involve three-dimensional (3D) objects such as solid object molding are yet to receive any significant attention. Recent work done by Kelkar et al. [19,20] constitutes the only work done with respect to the use of a reconfigurable tool for the purpose of molding 3D free-form objects.

A reconfigurable mold tool needs to have the ability to approximate all the outer surfaces of solid free-form objects due to which it would be different from all previous reconfigurable tools. The existing reconfigurable tools consist of only one or at the most two matrices of discrete pins. Though this is sufficient for applications such as forming where it is required to create a 2D surface, it is not suitable in molding processes where the need is to create a 3D solid object. To design a reconfigurable tool for molding processes, where the process loads may be higher, the pin-to-pin interaction has to be taken into account. In the case of forming and fixturing, the deflection of pins at the top was considered to be the indicator of the tool stiffness. For a reconfigurable tool to be used for solid object molding, this is not sufficient. The most important factor that will decide tool performance are the inter-pin gaps formed as this determines if the tool can bear the process loads while not allowing any molten material to leak out. Therefore, a new reconfigurable tool for molding needs to be designed and analyzed taking into account the individual as well as interactive behavior of its constituent pins and the gaps formed between the pins.

3. Design of the reconfigurable mold tool

3.1. Identification of the process conditions for the reconfigurable mold tool

To design a reconfigurable mold tool, the process conditions that the tool is subjected have to be identified. In terms of molding applications, process conditions will be similar to those in injection molding or open cast molding. Two types of reconfigurable mold tools that are conceived from the above-mentioned processes are the closed reconfigurable mold tool and the open reconfigurable mold tool.

The closed reconfigurable mold tool is closed from all sides to form a closed cavity similar to an injection molding tool. In addition to that, it will have similar high pressure and temperature conditions as an injection molding tool. To have complete control over the surface approximation along all the three axes, it requires at least six pin matrices, two along each of the axes to completely define a closed, solid object as shown in Fig. 2.

An open reconfigurable mold tool on the other hand, has a minimum of one matrix of pins, though at least five of them are required for a better surface approximation as shown in Fig. 3. In open reconfigurable molding, the only forces acting on the tool are due to the weight of the raw material.

The closed reconfigurable mold tool forms the main focus of this work due to harsher process conditions when compared to the open reconfigurable mold tool. The term reconfigurable mold tool will now onwards be used synonymously with closed reconfigurable mold tool for the rest of this paper. Drawing similarities from injection molding, the molten thermoplastic material is considered to be a dense liquid that exerts hydrostatic pressure on a closed mold cavity in all directions and is Newtonian in nature that follows Pascal's law of fluid pressures.

3.2. Behavior of the reconfigurable mold tool under process conditions

For the creation of various forms and features on the product molded out of the reconfigurable tool, the pins of the discrete pin matrices comprising the tool have to be repositioned relatively. This discrete nature reduces the rigidity of the tool and in turn decreases the stiffness of the tool. Therefore, tool behavior in terms of the pin matrices and the individual pins has to be properly understood and studied to design and analyze the reconfigurable mold tool under process conditions.

The discrete pin matrices will behave similar to mold pieces in an injection molding setup. In this paper, a cavity pressure of 30–40 MPa, which is more common in injection molding of thick walled parts, is used [21]. In the absence of sufficient constraints, this cavity pressure can act upon the mold pin matrices to separate them and cause the material to leak out leading to flashing on the molded part. The pin matrices need to be properly positioned with respect to each other and then held tightly together, so that gaps do not open up between the pins, causing the molten material to leak out as shown in Fig. 4(a). This calls for individual clamping units for each matrix of discrete pins. Using sufficient clamping force on the pin matrices will allow them to stay in their place and form the products.

The other issue that can affect the reconfigurable mold tool is the individual as well as the interactive behavior of the pins of the

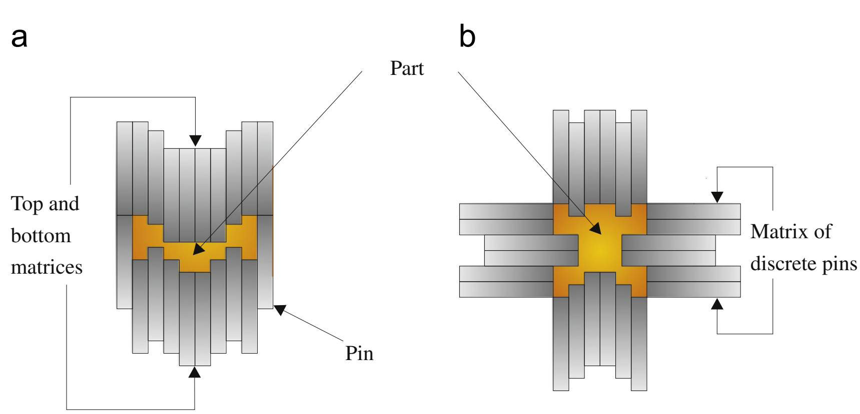


Fig. 2. Cross-sectional view of the closed reconfigurable mold tool: (a) 2-matrix setup and (b) 6-matrix setup.

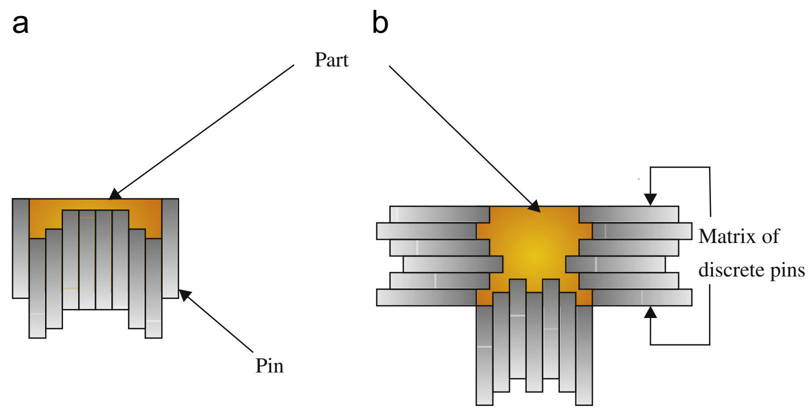


Fig. 3. Cross-sectional view of the open reconfigurable mold tool: (a) 1-matrix setup and (b) 5-matrix setup.

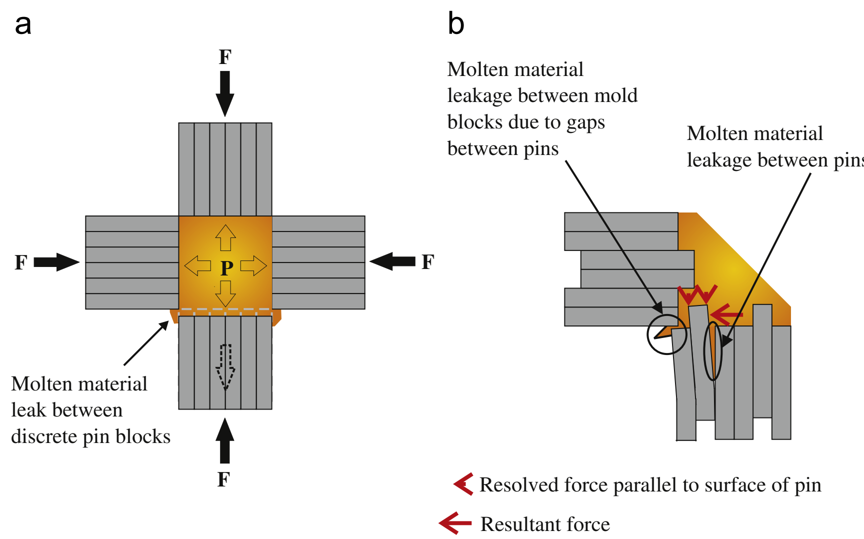


Fig. 4. Leakage of material between discrete pin matrices and between pins.

discrete pin matrices. In addition to this force, as in injection molding, a lot of pressure inequalities will arise in the mold cavity, from an initial mold filling stage followed by the packing stage to the final mold cooling stage. These pressure inequalities will act upon the discrete pins of the matrices and can displace, deflect and/or bend them. Gaps can open up between pin–pin interfaces and between the pin matrices as a result of the pressure loads, resulting in molten material flowing in between them and forming spikes on the outer surface of the object as shown in Fig. 4(b).

Therefore, some form of constraints are required to nullify the effect of the internal forces and to keep the pins and the pin matrices in a tightly held configuration. When the magnitude of the applied constraints are above a certain value, the pins are held tightly to each other and molten material will not leak between the pins, thereby preventing the formation of flashes.

3.3. Constraint-based improvement of the strength and integrity of the reconfigurable mold tool

Ideally, the pins have to be perfectly constrained, i.e., no bending, deflection or displacement, so that no gaps are formed between them. Based on the initial configuration of the tool, the integrity and strength on the macro as well as micro level of the tool are improved by placing the following constraints on the tool:

(1) use of a self-locking pin actuating mechanism;
(2) use of square shape for pin cross-sectional shape;
(3) use of clamping forces;
(4) use of supplementary support blocks.

The following sections detail the use of the above given constraints in improving the strength of the reconfigurable mold tool.

3.3.1. Use of a self-locking pin actuating mechanism

A pin actuating mechanism is required to move the pins to their required positions. With respect to molding, using a pin actuating mechanism that is self-locking in nature will help the pins to be constrained along their vertical axis. This is achieved by using a lead screw-based mechanism, though this would be restricted by the strength of the threads. A hydraulic-based system is not self-locking by default but can also be designed to be self-locking.

The use of a 3-axis numerical control (NC), lead screw-based sequential setup unit mechanism has been investigated to initiate pin movement as shown in Fig. 5. This mechanism consists of

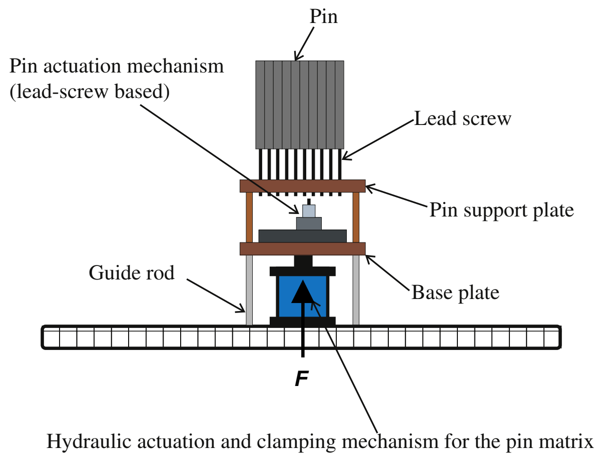


Fig. 5. Lead screw-based sequential setup unit for pin actuation.

three stepper motors for each matrix of pins, two of which are attached to slides to provide motion along the two horizontal axes. The first two motors work to take the third motor from one pin to the other while the third motor initiates pin movement. Such a system can carry out pin actuation irrespective of the size of pins unlike a shaft-driven mechanism or individual motors. Open-loop algorithms have been developed as a part of this work to raise or lower the pins in a zig–zag fashion to their positions. The pin positions can be determined by methods as developed by Kelkar et al. [19,20]. The algorithms carry out the sequential invocation of the NC commands based on the values of three binary variables. The pin lowering algorithm is a compliment of the pin raising algorithm and therefore is not presented.

There are three basic steps or NC commands, one for a single movement along each axis. The amount of movement along the horizontal axes is always the same, i.e., distance between the centers of any two adjacent pins. Hence, the NC commands to move the mechanism along each of the horizontal axes are always the same with only change in their direction as shown in Fig. 6.

For a matrix of m rows and n columns the minimum total number of such *steps* involved and the corresponding number of NC commands issued is calculated as follows (including movements in the vertical Z direction):

$$N=[(m+(m+2))\times n]+1=2mn+2n+1 \quad (1)$$

Algorithm 1. Algorithm: Pin Raising

INPUT: $z(i)$ where $i=1$ to $(m\ \times n)$: array of the 'Z' coordinate of pin final positions.
OUTPUT: NC command set to raise the pins to their final positions.
START
Initialize $A \Leftarrow 0$, $B \Leftarrow 0$, $C \Leftarrow 0$; **/**Boolean variables to control invocation of the NC commands**/**
Initialize *Counter* $\Leftarrow 0$;
Initialize $i \Leftarrow 0$;
Open (NC File);
NC command Invocation
For($i=1$ to N, i++) {/ ∗ ∗***N* is calculated from Eq.** (1)**/
If ($A=0$ and $B=0$ and $C=0$)
Then MOVE-BACKWARD-X1( );
Else If ($A=1$ and $B=0$ and $C=0$)
Then MOVE-BACKWARD-Y( );
Else If ($A=1$ and $B=0$ and $C=1$)
Then MOVE-UPWARD-Z1( );
Else If ($A=1$ and $B=1$ and $C=1$)
Then MOVE-BACKWARD-X2( );
Else If ($A=0$ and $B=1$ and $C=1$)
Then MOVE-FORWARD-Y( );
Else If ($A=0$ and $B=1$ and $C=0$)
Then MOVE-UPWARD-Z2( ); }
Close (NC File);
END
MOVE-BACKWARD-X1( ) {
Write (i“ ”X_B) to the NC output file; **/**X_B: NC command to move the distance between two adjacent pins along X axis in the backward direction***/**
$A \Leftarrow 1$; $B \Leftarrow 0$; $C \Leftarrow 0$;}
MOVE-BACKWARD-Y( ) {
Write (i“ ”Y_B) to the NC output file; **/**Y_B: NC command to move the distance between two adjacent pins along Y axis in the backward direction***/**
Counter ++;
If (*Counter*$=m+1$)
Then $A \Leftarrow 1$; $B \Leftarrow 1$; $C \Leftarrow 1$;
Else $A \Leftarrow 1$; $B \Leftarrow 0$; $C \Leftarrow 1$;}
MOVE-UPWARD-Z1( ) {
Write (i“ ”$Z_{UP}(z(i))$) to the NC output file; **/**$Z_{UP}(\boldsymbol{z}(\boldsymbol{i}))$: NC command to raise move the ith pin to its final position**/**
i++;
$A \Leftarrow 1$; $B \Leftarrow 0$; $C \Leftarrow 0$;}
MOVE-BACKWARD-X2( ){
Write (i“ ”X_B) to the NC output file;
$A \Leftarrow 0$; $B \Leftarrow 1$; $C \Leftarrow 1$; }
MOVE-FORWARD-Y( ) {
Write (i“ ”Y_B) to the NC output file;
Counter −−;
If (*Counter*$=0$)
Then $A \Leftarrow 0$ $B \Leftarrow 0$; $C \Leftarrow 0$;
Else $A \Leftarrow 0$; $B \Leftarrow 1$; $C \Leftarrow 0$;}
MOVE-UPWARD-Z2( ) {
Write (i“ ”$Z_{UP}(z(i))$) to the NC output file;
i++;
$A \Leftarrow 0$; $B \Leftarrow 1$; $C \Leftarrow 1$; }

3.3.2. *Use of square shape for pin cross-sectional shape*

Using a polygonal shape like square, triangle, hexagon, etc., for the pin cross-section allows the pins to be constrained rotationally along their vertical axis. To achieve uniform approximation, only polygons with equal sides are to be considered. Among these, the square shape by virtue of being the only one that allows load path isolation, as proved by Walzcyk and Hardt [4], is the ideal one for the cross-sectional shape of the pins of the reconfigurable mold tool. Load path isolation allows the transfer of force across a row of pins without any losses when subjected to clamping load, leading to uniformity in clamp force distribution.

3.3.3. *Use of clamping forces*

Clamping forces can be used to increase the rigidity of the reconfigurable tool. This can done by either mechanical or hydraulic means. Clamping forces for the reconfigurable mold tool are to be applied to both the pins and the pin matrices.

Depending on the number of pins used, the mold pin matrices might require the use of large value of forces to be moved and clamped to each other. To minimize the cost and effort associated with this it is proposed that one pin matrix be kept fixed and the others be moved against it. As the top matrix always requires the most amount of force to be moved or to be clamped, this pin matrix is fixed. As shown in Fig. 7, the side pin matrices and

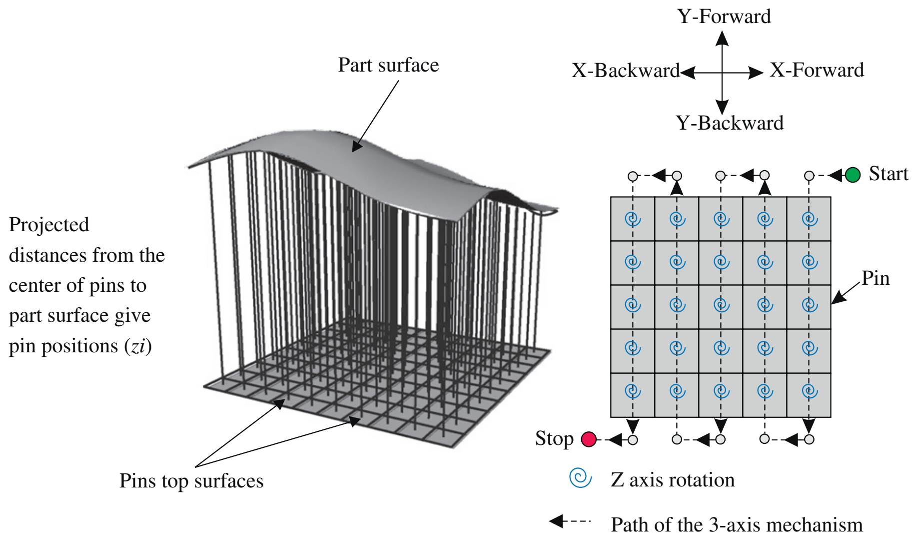


Fig. 6. Top view of the path taken by the 3-axis pin actuation mechanism.

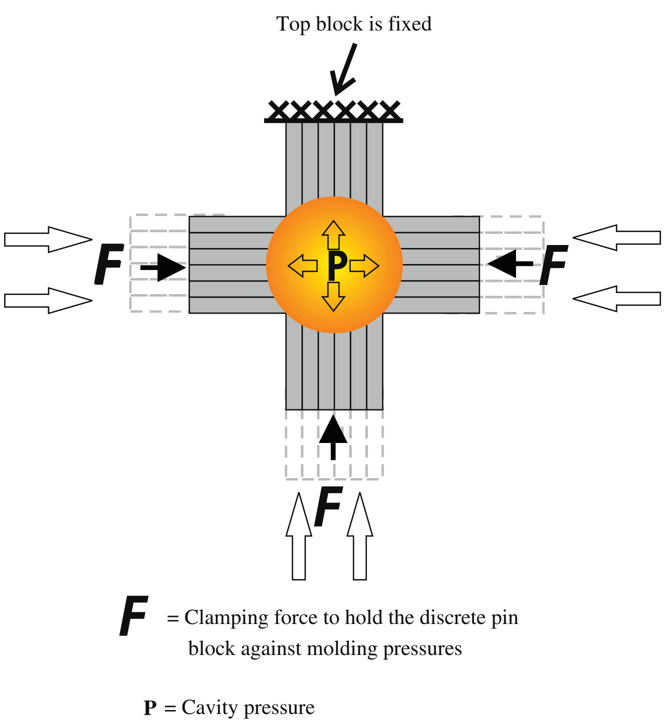


Fig. 7. Molding forces and clamping forces to counter them.

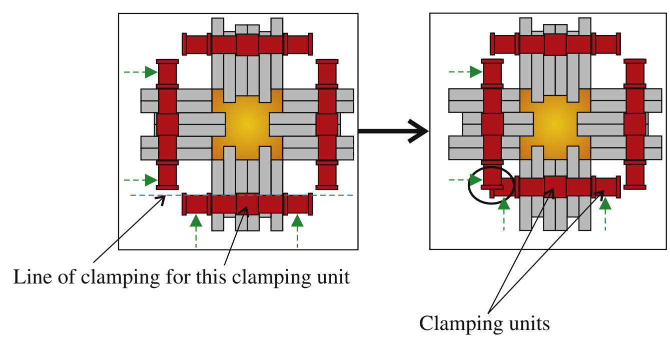


Fig. 8. 2D view of the space constraint affecting the position of clamping.

the bottom pin matrix will end up moving and clamping against the pin matrix that hangs upside down.

The calculations used to determine the amount of the clamping force to be applied on the discrete pin matrices to hold them together are similar to those used for injection molding tools [22]. The projected area, the area of the largest projection of the product at the parting line, A_{proj} of each discrete pin matrix is to be found out. The maximum of these projected areas, A_{max} is to be multiplied to the maximum cavity pressure that would occur in the mold, P_{max} to arrive at the minimum value of clamping force, F_{min} required to be applied to each matrix to prevent flashing:

$$F_{min} = A_{max} \times P_{max} \tag{2}$$

The nominal clamping force, which is the amount of force that is to be applied only after enough force has been applied to overcome the inertia of the weight of the discrete pin matrix setup, is be given by

$$F_{clamp} \propto F_{min} \tag{3}$$

$$F_{clamp} = k \times F_{min} \tag{4}$$

where k is the factor of safety whose value is usually ≥ 1.2.

The pins also are to be clamped laterally to bring them into a tightly packed configuration. Ideally the clamping has to be applied along the top of the pins of a discrete pin matrix. This prevents any deflection below the line of clamping and eliminates any gaps between the pins. Instead, there is a space restriction that forces the clamping to be applied at a certain distance below the top surface of the outermost pins. Any clamping unit occupies a certain volume and if two adjacent, perpendicular discrete pin matrices are each clamped at the top of their respective outermost pins, an interference arises in between the clamping units as shown in Fig. 8. Since the clamping can only be applied at some distance below the top of the pin, the deflection that takes place above the line of clamping cannot be prevented irrespective of the amount of clamping force. The following section presents a new method in the form of supplementary support blocks to laterally constrain the pins.

3.3.4. *Use of supplementary support blocks*

Adding a row of support blocks around existing pins has been proposed to prevent or minimize the deflection of the pins. Now the mere presence of a row of supplementary support blocks around the pins reduces deflection, but does not eliminate it. A symmetric, interlocking assembly of the pin matrices is proposed to achieve this, as shown in Fig. 9. In this arrangement the support pin arrangement for all the pin matrices is identical, which leads to uniform load distribution. They are divided into raised support blocks and lowered support blocks, where the raised support blocks are of the same length as that of the pins and the lowered support blocks are of the length equal to the length of pins minus the width of a support block. The pin matrices can be assembled in an interlocking arrangement if the top surface of a row of lowered support blocks mates with the side of a row of raised support blocks of an adjacent matrix at their top as shown in Fig. 10.

When the matrices are assembled in an interlocking arrangement, to ascertain that the matrices are aligned properly a cross-sectional view has been shown in Fig. 11(a). A Boolean, pair-wise intersection, operation is used to show the self-locking mechanism in 3D. The pair-wise intersection for a set of volumes is defined as the overlapping region of each pair of volumes in that set. Fig. 11(b) shows only areas and no volumes which indicates the absence of any form of volumetric interference between the matrices.

Based on the structural design of the tool, an example tooling system has been presented as shown in Fig. 12. Hydraulic actuated clamping units for the pin matrix have been shown that would be used to move the pin blocks and clamp them against each other. The support blocks are moved using the same mechanism as that used for moving the pins of their respective matrices.

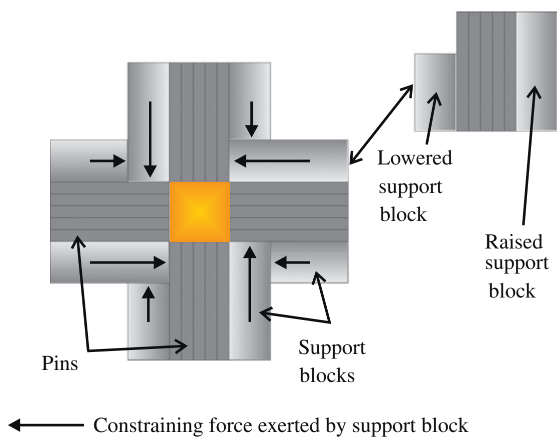


Fig. 9. Top view of the interlocking pin configuration, top matrix not shown.

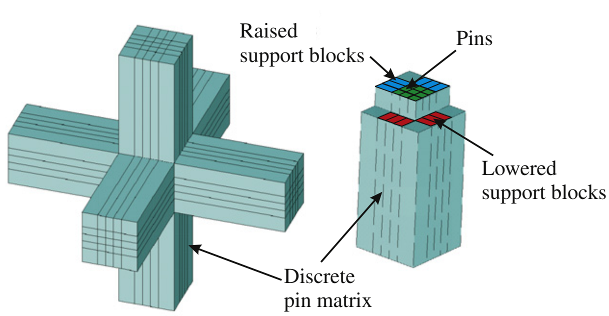


Fig. 10. 3D view of the interlocking pin configuration.

4. Structural analysis of the reconfigurable tool under process conditions

A structural analysis methodology is presented in this section that captures both the complex nature of the tool geometry as well as the pin–pin interaction. To carry out this analysis several assumptions are made. To carry out the analysis of the tool under given process conditions, the factors that would affect the performance of a reconfigurable tool when used for molding are identified as following and are also shown in Fig. 13:

(1) number of pins (n);
(2) pin cross-sectional size (w);
(3) pin-to-adjacent-pin height differential (h_i);
(4) pressure and temperature conditions of process (P, T);
(5) support block width (d);
(6) length of the pins (l).

The number of pins n used in a discrete pin matrix determines the tool size. The bounding box of the largest object to be made out of the reconfigurable tool decides the number of pins in the

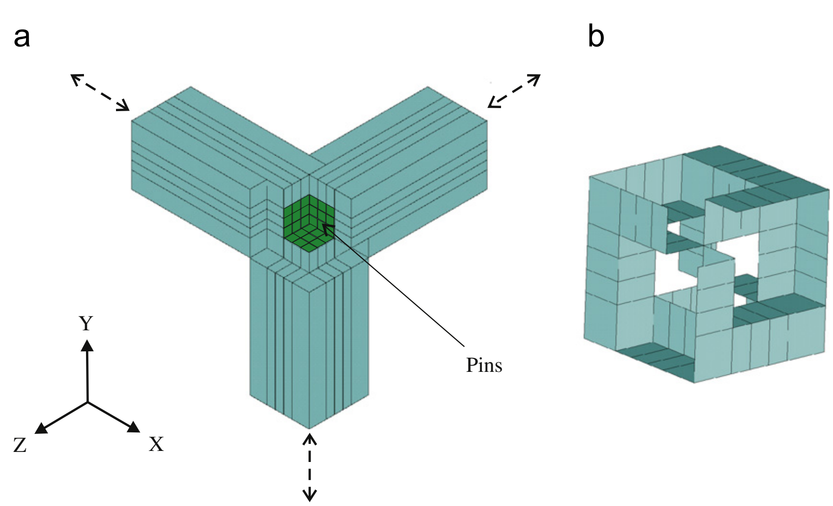


Fig. 11. Cross-sectional view and the pair-wise intersection of the interlocking pin matrix system. (a) Cross-sectional view of pin matrix interlocking system. (b) Pair-wise intersection between the discrete pin matrices.

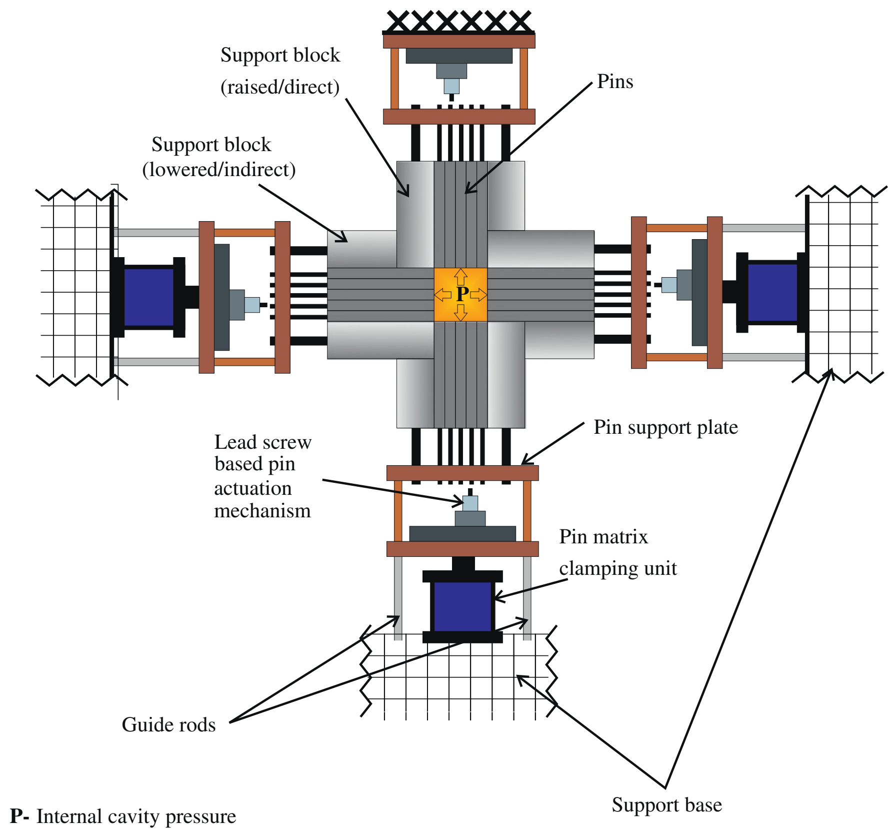


Fig. 12. Cross-sectional view of the reconfigurable mold tool system.

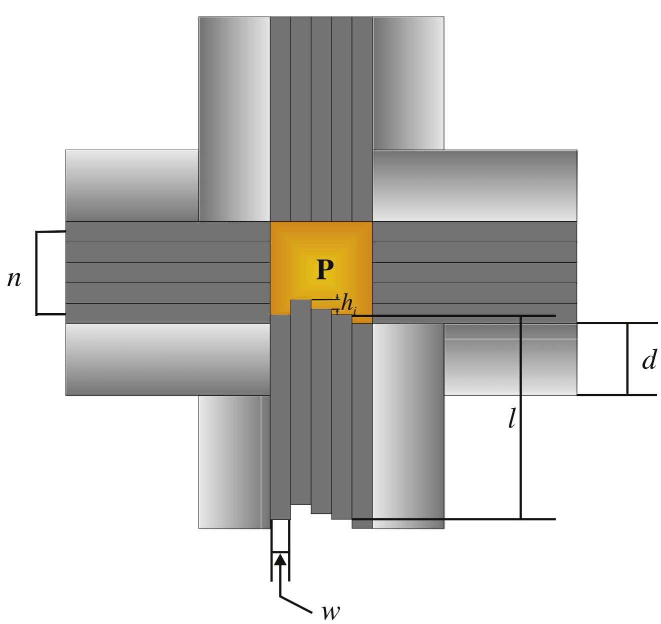


Fig. 13. Tool parameters.

tool based on the pin cross-sectional size. The pin cross-sectional size w on the other hand, not only decides the number of pins in a pin matrix as stated above, but also the approximation errors caused on the surface due to the discrete nature of the tool. The smaller the pin, the better the approximation and the lower the surface errors. The pin-to-adjacent-pin height differential h_i determines the complexity of design features that can be produced using the tool. A higher value of this factor allows more radical changes in surface curvature of the parts manufactured out of the tool. The pressure and temperature conditions are on the material being molded out of the tool and the size of the object being molded. Thinner objects entail higher pressures so as to allow the mold to be filled in the shortest possible time. The width of the support block d determines the amount of support extended to the pins to prevent them from deflecting. The magnitude of this factor has a maximum value equal to the difference in height between the top of a pin in its initial position and bottom of a pin in its highest possible position in a row. The length of the pin l not only influences the stiffness of the tool in a direct way, but also indirectly by the influencing the magnitude of the support block width. The longer the pin, the lesser is the stiffness of the pin but more is the magnitude of the support pin width, which could improve overall tool stiffness.

4.1. Structural analysis methodology for the reconfigurable mold tool

To assess the rigidity of the reconfigurable mold tool, it is necessary to study the tool behavior in terms of the size of the resultant gaps arising from pin deflection. Since a single tool can be reconfigured into many configurations, an analysis methodology is required to capture all possible configurations of the pins and the interaction between the pins of individual matrices. A static or time-independent finite element method (FEM) based simulation of the worst case of loading that the tool can undergo is developed with the involvement of lesser time, cost and computational efforts, while preserving the accuracy of the solution. FEM has the capability to handle complex structures as well as contacts between surfaces.

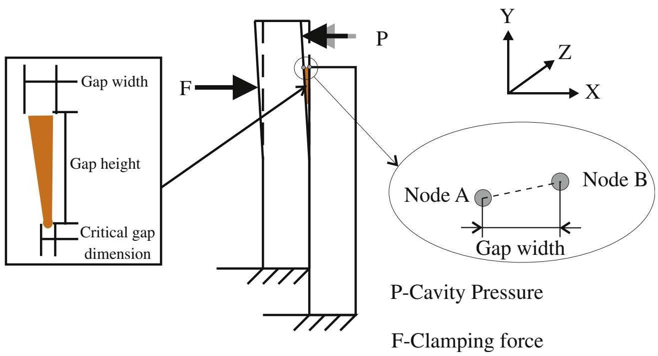


Fig. 14. Determination of the gap width.

The first task of the analysis process is to identify the worst case of loading that the reconfigurable mold tool can undergo. This is done for a single individual pin as well as an entire row of pins in the tool. After this is done, these scenarios are captured suitably in finite element models. The result of analyzing the worst case loading scenario is the magnitude of maximum gap that can occur in a reconfigurable mold tool of a particular specification under certain process conditions. The maximum gap is found from the maximum value of difference in the displacements experienced by the pair of nodes on the pins that share the same initial positions in the finite element model. In these pairs, one of the nodes has to be on the top surface of a pin. As shown in Fig. 14, Node A and Node B represent two such points and the difference of their displacements gives the magnitude of gap arising between their respective pins.

For the reconfigurable tool to be usable under a given set of process conditions, the value of gaps should be less than a certain critical value. In other words, the differential nodal displacements are considered significant enough only if the gap dimensions calculated are greater than the critical as shown in Fig. 14.

To assess the suitability of the reconfigurable mold tool for manufacturing 3D free-form objects under thermoplastic molding process conditions, a cavity pressure of 40 MPa is used [21]. In the case of injection molding, the fluid pressure acts normal to all surfaces of the tool. Considering that in the case of reconfigurable molding, it is assumed that all the forces due to the cavity pressure act only in the direction perpendicular to the vertical axis of the pins.

4.1.1. *Worst case loading scenario for a single pin in a pin matrix*

The worst case of loading a single pin can experience is when it protrudes out of the matrix, while all the other pins are at their lowest position. The protruding pin is positioned such that it receives least lateral support against molding pressures. The first condition for any arrangement of pins to be safe from flashing is found out from the maximum height h_{max} that a pin can protrude out of the array of pins. To be safe from leakage, for any configuration of the pins, none of the pin-adjacent-pin height differential h_i should be greater than critical value h_{max} for which the maximum gap value is greater than acceptable.

4.1.2. *Worst case loading scenario for an entire row of pins in the pin matrix*

The above given condition is not the only condition of tool stability. The appraisal of the tool performance is completed by considering the positions of the pins of an entire row of pins. The pins are arranged in a step-wise fashion where starting from the outermost pin, each pin rises above its adjacent pin by a constant distance h_{row} till the middle pin and then steps down till the pin at the other end of the row. The pins on only one side of the tool are loaded on areas of protrusion in the direction towards the middle pin to represent the worst possible case of loading on an entire row of pins. All the pin-to-adjacent-pin height differentials are the same which enables generalization of the model. The incremental accumulation of forces that takes place on each step down toward the last pin, adds on to the pin deflection and results in the possibility of bigger gaps formed in the tool for even when all values of pin-to-adjacent-pin height differentials would be lesser than h_{max}.

Therefore the conditions that a particular configuration of the pins would not yield a value of gap higher than a certain critical value are given as following:

If all the pin-to-adjacent-pin height differentials h_i for any configuration of the pins are lesser than or equal to h_{max} and the total of all the pin-to-adjacent-pin height differentials is lesser than or equal to the total of the pin-to-adjacent-pin height differentials of the worst-case model for an entire row of pins, then that particular pin configuration would be safe from failure.

$$h_i \leq h_{max} \tag{5}$$

$$\sum h_i \leq [(n-1) \times h_{row}] \tag{6}$$

where $i = 1$ to $(n-1)$.

4.2. *Structural modeling using FEM software*

The FEA package ANSYS version 6.1 from ANSYS, Inc. was used for modeling and conducting the structural analysis. The structural modeling and analysis methodology presented as a part of this paper is a general one and can be applied to other FEM software packages as well.

The top-down modeling approach is used to model the pin structure with the areas of loading. Using such a modeling approach, the final shape is arrived by first creating primitives (volumes or areas) and following it by the use of some Boolean operation(s) (add, subtract, intersect, divide, etc.). The finite element method, due to its discrete nature is susceptible to a certain amount of error which is dependent on the density and type of meshing used. A denser mesh guarantees an improvement in the accuracy of the solution, but at the cost of increased computational complexity, i.e., the time required to solve it. The 3D contact between the pins is modeled in ANSYS 6.1 by defining contact pairs using surface–surface contact elements. The areas including the bottom surfaces of all the pins are constrained linearly along all the three degrees of freedom. The pins are loaded on the areas created by volume division in the direction towards the middle of the tool. The output of the analysis is be the size of the biggest gap that would be formed in the tool due to pin deflection.

4.3. *Effect of tool parameters on the tool performance in terms of maximum gap dimension*

A structural analysis methodology based on the finite element method has been developed to study the behavior of the reconfigurable mold tool under process conditions of injection molding. The worst case of loading for a single pin in a matrix and an entire row of pins in a matrix is used to arrive at conditions that determine the capability of a tool to perform under given process without incurring leakage of material. Factors that affect the performance of a reconfigurable mold tool such as the width of support blocks, the length of the pins, the pin-to-adjacent-pin height differential, the pin cross-sectional size and the number of pins have been identified and their effects are presented in this section.

The aim is to achieve the maximum possible values of h_{row} and h_{max} under the given tool parameter limits without incurring a gap that would be large enough to allow molten material to leak between the pins. To do this, the effects of the factors affecting the tool performance are studied. The gap dimensions can be controlled by the following:

(1) increasing the width of the support blocks;
(2) increasing or decreasing the length of the pins;
(3) decreasing the pin-to-adjacent-pin height differential;
(4) increasing the pin cross-sectional size;
(5) reducing the number of pins.

The changes that can be made to the values of these three factors are limited by the interdependence of these factors on one another. Simulations have been carried out to depict the effect of the factors affecting the performance of the reconfigurable mold tool.

4.3.1. Effect of the width of the support blocks

The width of the support block d can be increased to improve the tool stiffness till there is space to do so. Though an increase in the support block width can increase the strength of the tool this can be done only until its value remains less than or equal to the height difference between the top of a pin in its initial position and bottom of a pin in the highest possible position in a row, which in itself is dependent on the length of the pin l, the pin-to-adjacent-pin height differential h_{row} and the number of pins n. After FEA and simulations under different conditions, the results are obtained and shown in Fig. 15. It can be seen from Fig. 15 that the maximum gap dimension reduces from 0.1043 mm for a support block size of 25–0.0642 mm for a support block size of 150 mm. The reduction is more sharp in the beginning but goes on to be lesser towards the end of the curve. The maximum possible support block size in this case is 160 mm, where the support block would occupy the entire length of the pin it is directly supporting.

4.3.2. Effect of the length of pins and the pin-to-adjacent-pin height differential

A reduction in the pin length l may not necessarily lead towards the improvement of the tool strength and decrease in the gap dimensions. A reduction in the length of the pin can be done in favor of increasing the tool rigidity. This can be done only till it does not result in the reduction of the support pin width d which could lead to an increase in gap dimensions increase. Further reduction of the magnitude of pin length reduces the support extended to the pins and therefore increases the gap dimensions.

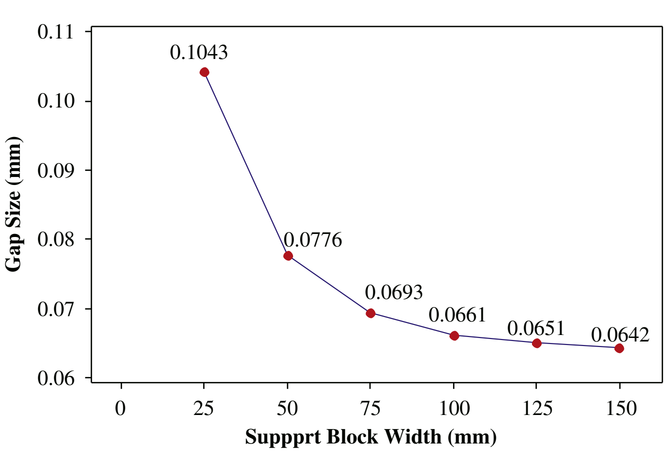


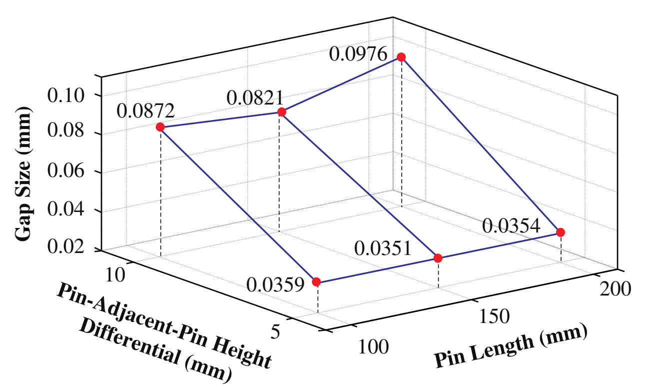
Fig. 15. Effect of the support block size on the maximum gap size.

This can be seen in Fig. 16, where the maximum gap values reduce as the pin length is reduced from 200 to 150 mm while it increases when it is further reduced to a value of 100 mm. While the 200 and 150 mm pin length permit the use of a 100 mm support block, the maximum width of support block possible in the case of the 100 mm pin is only 60 mm.

Decreasing the pin-to-adjacent-pin height differential h_{row} should be the last resort among all. This could improve the tool strength by decreasing the force applied on the tool by reducing area subjected to loading and by also allowing the use of a wider support pin but all at the cost of reduction in the complexity of features that can be achieved with the tool. The effect of increasing the pin cross-sectional size can be seen from Fig. 16 where the maximum gap values for $h_{row} = 10$ mm are higher than those for $h_{row} = 5$ mm.

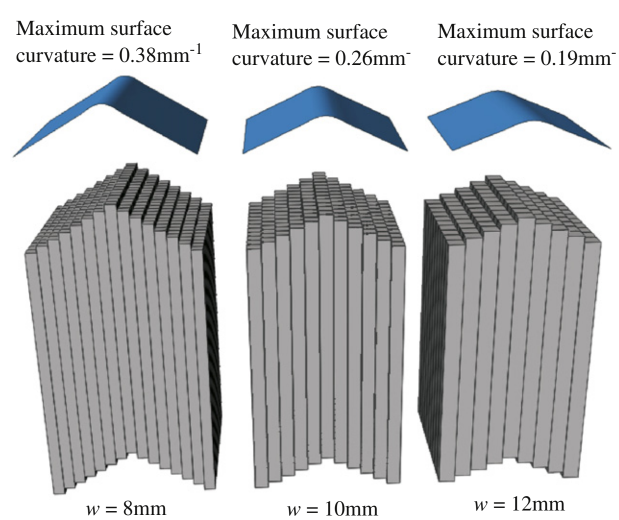
4.3.3. Effect of the pin cross-sectional size

As the pin size w reduces, for the same tool size and pin-to-adjacent-pin height differential h_{row}, the approximation done by the tool improves due to better surface control done by the tool. This can be seen in Fig. 17, where as the pin cross-section is reduced from 12 to 8 mm, the maximum surface curvature that



(w = 10mm, d = 100mm {*60 mm for l = 100mm}, n = 9, P = 40MPa)

Fig. 16. Effect of the length of pins and the pin-to-adjacent-pin height differential on maximum gap size.



(h_{max} = 5mm, Tool Size (n x w) = 120mm)

Fig. 17. Effect of the pin cross-sectional size on surface control.

can be approximated on the product surface increases from 0.19 to 0.38 mm^{-1}, respectively.

This improvement in surface approximation though comes at the cost of an increased gap dimension. As shown in Fig. 18, as the maximum gap dimensions increase from 0.0638 to 0.0341 mm, respectively. This is because the pin strength and hence the tool strength decreases with reduction in pin size.

4.3.4. *Effect of the number of pins*

Keeping the pin-to-adjacent-pin height differential constant h_{row} along with other process and tool parameters, if the number of pins n is increased to the next number of odd pins, the tool size increases and the maximum gap values produced also increases. This is caused by the increase in the area of loading with increases the magnitude of loading on the tool. This is shown in Fig. 19 where with an increase in tool size starting from 90 to 150 mm, the maximum gap dimensions increase from 0.0351 to 0.0617 mm, respectively.

4.4. *Discussion of the results from the structural analysis*

It is assumed that the structural behavior of the pins in the reconfigurable mold tool follows that of cantilever beams. Thermal loads and their effects are not taken into consideration. The pins are assumed to be perfectly arranged in accordance to the interlocking arrangement and perfectly flat with no gaps present between the pins before the application of forces. The pins are only loaded laterally and tool deformation is assumed to take place due to pin deflection only.

The structural analysis approach presented considers loads applied to the tool in the form of molding pressures only. A future development of the work will be the consideration of temperature loads in addition to pressure loads. Moreover, the pins are assumed to be completely flat, smooth and perfectly arranged such that before the application of any form of loads, there are no gaps present in the tool, which may not be true in a practical case. In addition to the structural design, other important parts of a typical molding system such a cooling system, runners and gates and venting schemes would have to be developed to obtain a fully functional reconfigurable tooling system for manufacturing solid, free-form objects.

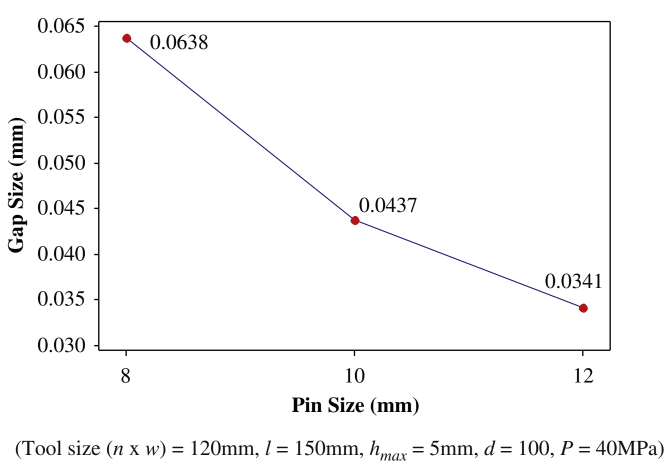


Fig. 18. Effect of the pin cross-sectional size on the maximum gap size.

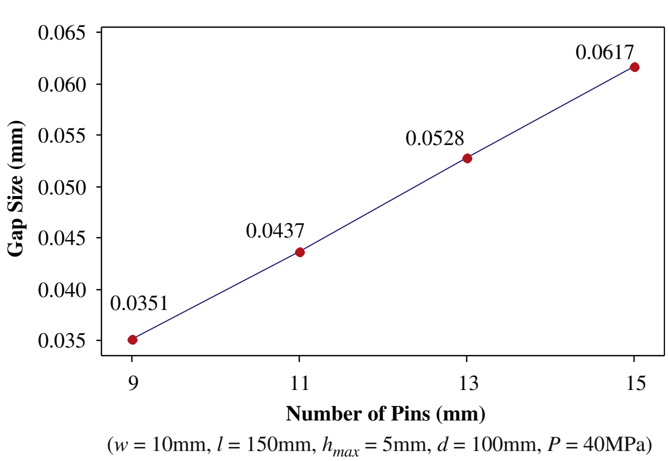


Fig. 19. Effect of the number pins on the maximum gap size.

5. Case studies and prototype implementation

5.1. *Case studies of implementation of the analysis procedure*

This section provides several examples of the implementation of the conditions developed as a part of the structural analysis to analyze tool strength. The maximum pin protrusion height is obtained for the worst case of loading of a single pin in a pin matrix. Fig. 20 shows the pin protrusions height h_{max}'s for the single pin worst case loading model with the corresponding maximum gap size. The tool consists of $n=9$ pins, each of cross-sectional size $w=10$ mm and length $l=150$ mm. The width of the support block d used is 150 mm. The tool is subjected to a pressure P of 40 MPa. From the worst case of loading of an entire row of pins, a maximum pin-to-adjacent-pin height differential h_{row} is found to be 5 mm. The total of the pin-to-adjacent-pin height differentials $[(n-1)\times h_{row}]$ for the nine pin tool is calculated to be 40 mm. Four example cases are compared for the maximum gap dimensions with the h_{max} and $[(n-1)\times h_{row}]$ of the worst-case models and the tool capability conditions are applied to assess the tool strength under process conditions. Young's Modulus E of the material of pins is taken to be equal to that of steel, i.e., 2×10^5 MPa. A critical gap value of 0.05 mm is used, which is arrived from the depth of the largest vent that an injection mold can accommodate when ABS plastic is the material being molded without any leakage, as provided by Bryce [23]. The results are shown in Table 1.

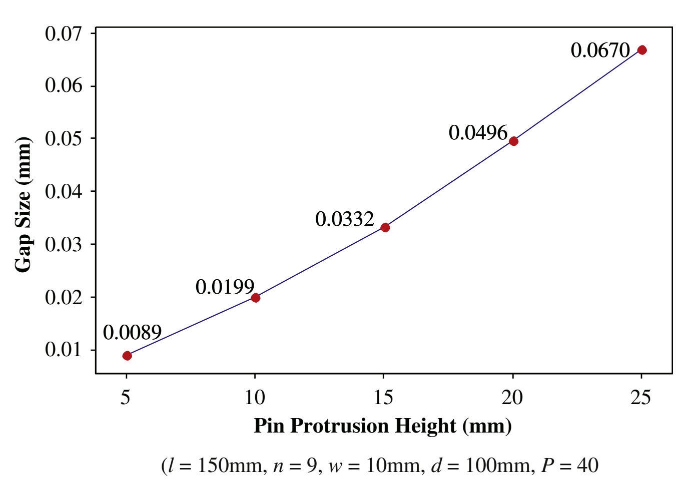


Fig. 20. Effect of the pin protrusion height on the maximum gap size.

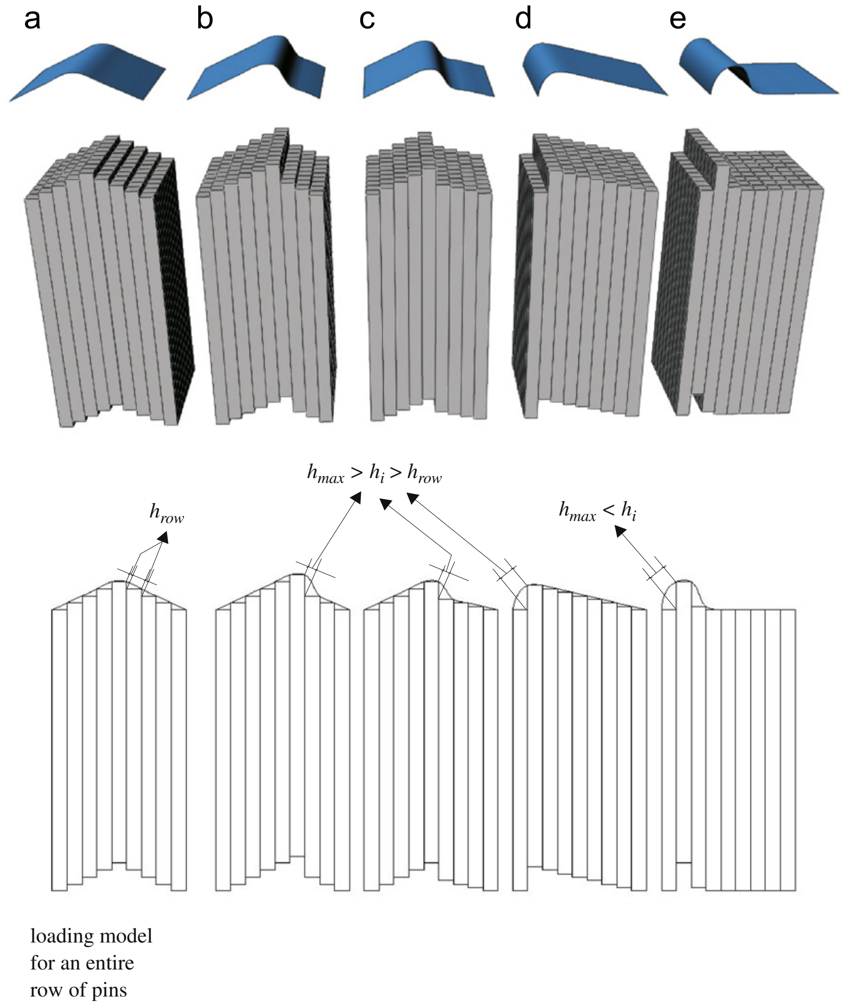


Fig. 21. Comparison of example cases to worst-case model of an entire row of pins. (a) Worst case loading model for an entire row of pins. (b) Case 1. (c) Case 2. (c) Case 3. (d) Case 4.

Table 1
Maximum gap sizes for various cases in comparison to the worst-case model.

Maximum gap size in (mm) Worst-case model (entire row of pins)	Case 1	Case 2	Case 3	Case 4
0.0351 $n=9$, $w=10$ mm, $l=150$ mm, $d=100$ mm, $h_{row}=5$ mm, $P=40$ MPa, $E=2\times10^5$ MPa	0.0453	0.0346	0.0301	0.0220

In Case 1, one or more of the pin-to-adjacent-pin height differentials h_i is greater than h_{row} but not greater than h_{max}. In addition to this, the total of h_i's is greater than the total of the pin-to-adjacent-pin height differentials of the worst-case model for an entire row of pins as shown in Fig. 21. This violates the second condition for tool stability given by Eq. (6). Fig. 21(b) shows this case and the maximum deflection is found to be more than that of the worst-case model, making it susceptible to failure.

For Case 2, the total of pin-to-adjacent-pin height differentials is equal to the total of the pin-to-adjacent-pin height differentials of the worst-case model. This is accompanied by the fact that one or more of the h_i's in the model is greater than h_{row}, though less than h_{max}. This is shown in Fig. 21(c) and the maximum deflection is found to be less than that of the worst-case model.

The total of pin-to-adjacent-pin height differentials for Case 3 is lesser than the total of all the pin-to-adjacent-pin height differentials of the worst-case model of an entire row of pins. Even here, one or more of the h_i's is greater than h_{row} and all of them are less than h_{max}. The maximum deflection is found to be less than that of the worst-case model, therefore signaling a safe case.

In Case 4, even though the total of pin-to-adjacent-pin height differentials is lesser than the total of all the pin-to-adjacent-pin height differentials of the worst-case model, one or more pin-adjacent-pin height differentials h_i are greater than h_{max}. The h_{max} can be interpolated from Fig. 20 to be around 15.6 mm, whereas the largest value of h_i in this case is 17 mm. Even though the actual evaluation of the case shows a safe value of maximum gap size, it would still be deemed unsuitable as a result of the violation of the first condition for tool capability given by Eq. (5) (Table 1).

5.2. Prototype open reconfigurable mold tool and sample parts

A prototype reconfigurable mold tool has been developed as a part of this work (see Fig. 22) to demonstrate the capability of molding 3D objects using reconfigurable tooling. The prototype consists of a 25 (5×5) pin matrix, in which the pin movement is automated using a 3-axis lead screw-based sequential setup

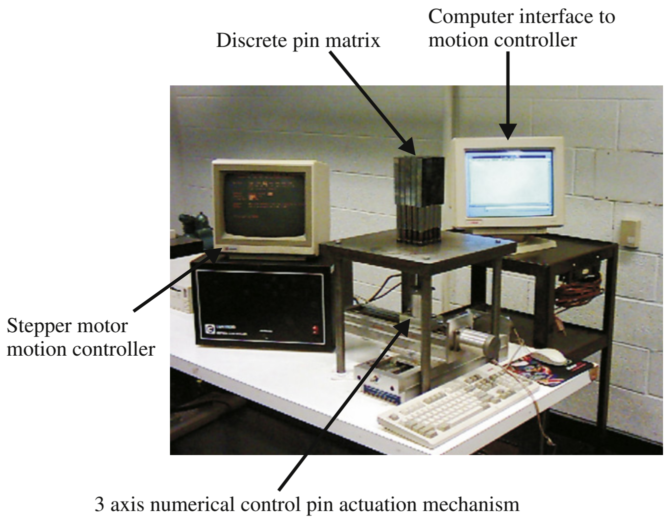


Fig. 22. Prototype reconfigurable mold tool.

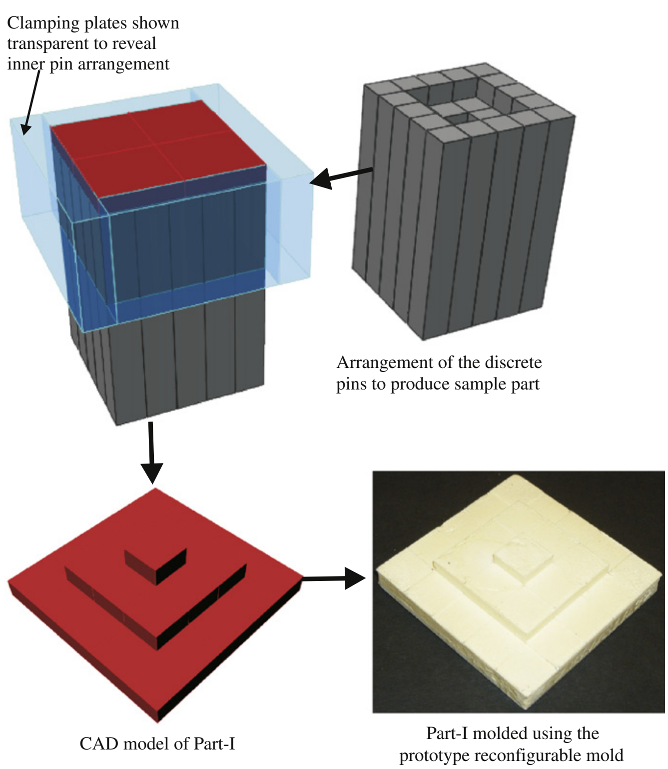


Fig. 23. Sample part fabricated using prototype reconfigurable mold tool.

mechanism. The pins are square-shaped in cross-section of size 19 mm and of length 127 mm. They are made out of mild-steel and finished using surface grinding and chrome-plating. Clamping plates are used to hold the pins tightly together and also to form side walls for cavities to be formed out of the tool. This reconfigurable mold tool is open from the top to allow material to be introduced into the cavity.

Example parts made of polyurethane were fabricated to illustrate the capability of producing 3D solid parts. Fig. 23 shows the such a part along with its CAD model. The pins can be reconfigured to get a completely different part as shown in Fig. 24.

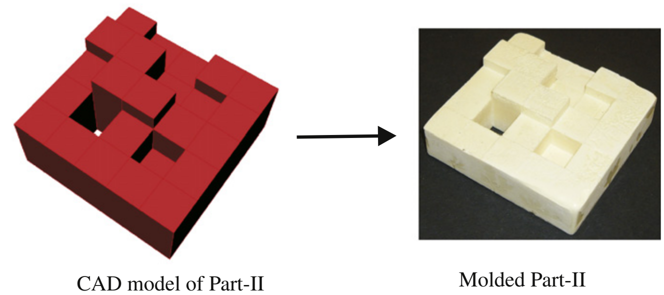


Fig. 24. Completely different part obtained using same tool.

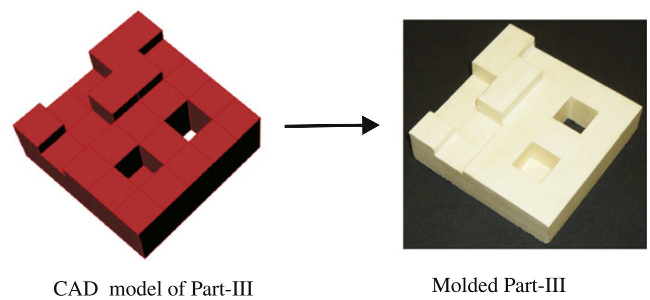


Fig. 25. Variant of the existing part.

Geometrically and dimensionally similar variants of existing parts can be molded using the same tool as shown in Fig. 25 thus eliminating the need for new sets of tools. The parts can also be subjected to operations such as machining to enhance the finish of the outer surfaces (as shown in Fig. 25).

6. Conclusions

This research presents the design and analysis of a new discrete pin-based reconfigurable tooling system for manufacturing 3D free-form objects. The proposed reconfigurable tooling system is expected to reduce the lead time and costs associated with new tool development in molding processes. This would help mass customization of products by enabling the use of a single tool to produce geometrically and dimensionally similar variants of a product.

The design of the tool is based on the structural rigidity of the tool. The reconfigurable tool, due to its discrete nature is weaker than a conventional tool that is solid in nature. The main challenge is to design a tool that can be used under process conditions without the occurrence of any gaps in the tool due to tool deformation. Several methods of constraining the tool to prevent gap formation are presented. Once the constraints are placed on the tool, the tool strength is analyzed using a finite element method (FEM) based procedure. Factors that affect the tool deflection and lead to gap formation are identified and their effects are illustrated. In addition to this, conditions are defined to determine if any arrangement of the pins in a matrix of pins would be safe from leakage under given process conditions. These conditions are based on the worst cases of loading that a single pin in matrix of pins and that an entire row of pins can undergo. The tool performance has been analyzed under the process conditions of injection molding and several implementations have been presented.

A prototype reconfigurable open molding setup has been used to carry out practical implementation to produce sample parts to prove the tool capability. The pin actuation is automated using a 3-axis numerical control, lead screw-based mechanism. Open loop pin raising and pin lowering algorithms are developed as a part of the work to automate pin actuation.

To produce parts with free-form surfaces reconfigurable tools might require some form of complementary interpolating medium or finishing operations. Despite this, their biggest advantage in the form of their rapid reconfigurability, leading to the creation of new tools from a single tool within very less time, makes them a very exciting prospect in the rapid, low-cost tooling category.

References

[1] Wang A, Koc B, Nagi R. Complex assembly variant design in agile manufacturing. Part I: system architecture and assembly modeling methodology. IIE Transactions on Design and Manufacturing 2005;37(1):1–15.

[2] Wang A, Koc B, Nagi R. Complex assembly variant design in agile manufacturing. Part II: assembly variant design methodology. IIE Transactions on Design and Manufacturing 2005;37(1):17–33.

[3] Altan T, Lilly B, Yen YC. Manufacturing of dies and molds. Annals of CIRP 2004;2:405–24.

[4] Walczyk DF, Hardt DE. Design and analysis of reconfigurable discrete dies for sheet metal forming. Journal of Manufacturing Systems 1998;17(6):436–54.

[5] Walczyk DF, Hosford JF, Papazian JM. Using reconfigurable tooling and surface heating for incremental forming of composite aircraft parts. Journal of Manufacturing Science and Engineering 2003;125(2):333–43.

[6] Munro CB, Walczyk D, Dvorak G, Slusarski SJ. Incremental double diaphragm forming of composite materials using reconfigurable tooling. In: NAMRC Thirty Two, Charlotte, North Carolina; 2004. p. 1–7.

[7] Kleespies HS, Crawford RH. Vacuum forming of compound curved surfaces with a variable geometry mold. Journal of Manufacturing Systems 1998;17(5):325–37.

[8] Dickens PM. Principles of design for laminated tooling. International Journal of Production Research 1997;35(5):1349–57.

[9] Pepelnjak T, Kuzman K. Adaptable tooling sets for metal forming of geometrically similar products. Journal of Materials Processing Technology 1998;80–81:413–20.

[10] Soar R, Dickens P. Design limits of unbonded laminate tooling for pressure die-casting. Proceedings of the Institution of Mechanical Engineers Part B 2001;215:531–43.

[11] Walczyk DF, Hardt DE. Rapid tooling for sheet metal forming using profiled edge laminations—design principles and demonstration. Journal of Manufacturing Science and Engineering 1998;120:746–54.

[12] Im YT. The development of a rapid tooling system for profiled edge lamination dies and molds. Phd thesis, Rensselaer Polytechnic Institute; 2001.

[13] Shook J. The development of a general element modeling method for profiled edge laminated tools. Master's thesis, Rensselaer Polytechnic Institute; 2002.

[14] Shook JT, Walczyk DF. Structural modeling of profiled edge laminate (pel) tools using the finite element method. Journal of Manufacturing Science and Engineering 2004;126(1):64–73.

[15] Walczyk DF, Lakshmikanthan J, Kirk DR. Development of a reconfigurable tool for forming aircraft body panels. Journal of Manufacturing Systems 1998;17(4):287–96.

[16] Walczyk DF, Im YT. A hydraulically-actuated reconfigurable tool for flexible fabrication: implementation and control. Journal of Manufacturing Science and Engineering 2000;122(3):562–8.

[17] Im YT, Walczyk DF, Schwarz RC, Papazian JM. A comparison of pin actuation schemes for large-scale discrete dies. Journal of Manufacturing Processes 2000;2(4):247–57.

[18] Walczyk DF, Longtin RS. Fixturing of compliant parts using a matrix of reconfigurable pins. Journal of Manufacturing Science and Engineering 2000;122(4):766–72.

[19] Kelkar A, Nagi R, Koc B. Geometric algorithms for rapidly reconfigurable mold manufacturing of free-form objects. Computer-Aided Design 2004;37(1): 1–16.

[20] Kelkar A. Geometric analysis and planning of hybrid manufacturing system using re-configurable molding and multi-axis machining. Master's thesis, State University of New York at Buffalo; 2004.

[21] Rees H. Understanding injection mold design. Cincinnati: Hanser/Gardner Publications; 2001.

[22] Rees H. Mold engineering. Hanser/Gardner Publications; 1995.

[23] Bryce MD. Plastic injection molding: mold design and construction fundamentals, volume III: fundamentals of injection molding series. Society of Mechanical Engineers; 1998.